Multiple Equilibria in the Urban Spatial Structure: Evidence from the Hanshin Earthquake

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Abstract: Despite the theoretical predictions that multiple equilibria exist in urban spatial structure, there remains a dearth of related empirical literature. This study adopts the 1995 Hanshin earthquake, which devastated the major city of Kobe (Japan), as a natural experiment to investigate the existence of multiple equilibria. Using municipality-level population data for the period of 1988–2011 and synthetic control approach, the analysis reveals that 16 years after the earthquake, the urban spatial structure in quaked areas persistently differs from the pre-quake pattern, although the total population recovered. Because of the seismic damage to Kobe, residents from around it migrated to areas close to Osaka, another major city close to the epicenter but less damaged. The major motivation underlying the migration is the demand for services provided in major cities. This tendency was not reversed even after Kobe was reconstructed, because the equilibrium of population dynamics moved to a new steady state.

Keywords: multiple equilibria; natural disaster; urban spatial structure; synthetic control approach

JEL classification: R12; R23; O18

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1 Introduction

The spatial distribution of population and economic activities is determined by not only fundamentals but also multiple equilibria, a key feature explaining economic locations in the traditional urban theory (Fujita and Ogawa, 1982) and new economic geography (Krugman, 1991; Fujita et al., 1999). However, there is a lack of empirical evidence on the multiple equilibria of economic locations, because related tests require large and temporary shocks caused by, for example, political conflicts, or large-scale natural disasters, which are rare.

Bosker et al. (2007) find evidence on multiple equilibria in Germany's urban system, that is, urban system does not return to its initial distribution after a major shock from World War II. Their results, however, remain unclear whether this phenomenon can be attributed to a change in fundamentals or a move to multiple steady states, their conclusion is subject to the assumption of unchanged fundamentals. Focusing also on Germany, Redding et al. (2011) examine the development of its airports during 1927–2002 and identify the shift of the air hub from Berlin to Frankfurt as the multiple equilibria in industrial locations. Davis and Weinstein (2002; 2008), by contrast, find the fundamentals but not multiple equilibria play the key role in the post-World War II population and industrial dynamics of Japan. However, Bleakley and Lin (2012) argue the conclusions by Davis and Weinstein (2002) are partly subject to the heterogeneity in natural features of Japan, the rugged topography of Japan perhaps precludes the possibility that there exist multiple equilibria.

Existing empirical studies on multiple equilibria tend to focus on the spatial scale of a country. By contrast, this study is conducted on a local spatial scale, that is, in a metropolitan area (MA). The merit of this setting is to have a clear observation of population dynamics and identification of exogenous shock, since a sudden event tends to have a more significant impact in local areas than the nationwide (Barone and Mocetti, 2014). Adopting the Hanshin earthquake in Japan (January, 1995), which severely devastated the city of Kobe, as the setting for a natural experiment, I investigate the long-term consequences of a natural disaster on the urban spatial structure and its underlying mechanisms. In doing so, I attempt to answer three questions: Has the quaked areas recovered from the post-quake population loss?[1] Do the quaked areas show a homogeneous path of recovery? Do the multiple equilibria in urban spatial structure work as the underlying channel for post-disaster population recovery?

Prior to conducting the empirical analysis, I set up a theoretical model on population dynamics in a MA that suffers a massive earthquake. The model suggests that proximity to a major city can be a key factor in determining the residential location within a MA, because specific services demanded by residents are largely provided in major cities. Thus, when a major city is significantly devastated by an earthquake, residents from around this city are more likely to migrate toward the next nearby major city that is less affected. Given the density economies of the service industry, it is possible that the reshaped population distribution remains in the steady state, even after the destroyed major city has recovered.

I adopt the synthetic control approach (see a detailed instruction in Abadie et al., 2010) using municipality-level residential population data to observe post-quake population dynamics by comparing with the synthetic control units in non-quaked areas. I find that the post-quake population dynamics are in line with the implication of the present theoretical model. In quaked areas, the intra-regional spatial structure in the residential location persistently changed compared to the case without the quake, although Kobe was quickly reconstructed, and total population was recovered within 16 years. More specifically, 16 years after the disaster, there was an 8.3% growth in population in the east side of the quaked areas (close to Osaka, another major city close to the epicenter but less affected by the earthquake), while the west side (remote from Osaka) suffered a 10.4% drop. Municipalities in the quaked areas show an agglomeration with Osaka owing to the destruction in Kobe. The new population growth path for spatial structure is concluded as the combined effect of density economies in the service industry and the migration cost of residential location.

[1] A series of empirical studies find that the net effects of a natural disaster and war destruction on the long-term economic depression and population are negligible. See Xiao (2011), Strobl (2011), Cavallo et al. (2013), and Husby et al. (2014) for the effects of natural disaster and Davis and Weinstein (2002, 2008), Brakman et al. (2004), Bosker et al. (2008), and Miguel and Ronald (2011) for the impact of wars. In addition, Barone and Mocetti (2014) find that an earthquake has a positive (negative) effect on the long-term GDP per capita growth if the post-quake large-scale financial aid improves (deteriorates) local institutional quality. Similar with this study in terms of spatial scale, Siodla (2015) exploits the impact of large exogenous shock on long-term evolution of urban land-use taking the 1906 San Francisco Fire as a natural experiment; razed areas are found to have higher population density compared with unburned areas because of urban redevelopment. By utilizing the synthetic control method, duPont and Noy (2015) find the long-term costs of Hanshin earthquake are hidden when focusing on direct and short-term costs.

To provide unbiased estimates, I also conduct regressions on population dynamics by incorporating the identification on earthquake, proximity to major city, and additional control variables: degree of destruction and the probability of an earthquake in the near future, among other factors. In addition, I discuss the impact of an earthquake on long-term residential and commercial land prices.

This study contributes to the literature in two aspects. First, I provide empirical evidence of multiple equilibria in urban spatial structure, following Bosker et al.'s (2007) findings on the national urban system and Redding et al.'s (2011) concept of industrial location, which is still scarce. In contrast to the existing estimates, this study focuses on the determinate of residential location within a metropolitan area,[2] that is, a local spatial scale, but not a cross-regional spatial scale. As suggested by Barone and Mocetti (2014), a sudden event tends to have a more significant impact in local areas than the nationwide. Second, this paper follows Horwich (2000) and duPont and Noy (2015) on the evaluation of post-Hanshin earthquake recovery.[3] The same with duPont and Noy (2015), I apply the synthetic control approach to estimate the counterfactual growth path in quaked areas. The major difference is on the focus of administrative units. duPont and Noy (2015) estimate the long-term impacts of Hanshin earthquake based on the aggregate (i.e., prefecture level) economic and population indicators, while my estimates exploit both the aggregate and the disaggregate (i.e., municipality level) recovery dynamics. The results reveal a significant heterogeneity on the post-quake population dynamics within the quaked areas, which tends to be hidden in an aggregate analysis.

The remainder of this paper is organized as follows. Section 2 introduces the Hanshin earthquake. Section 3 presents the theoretical framework. Section 4 provides the empirical strategies. Sections 5 and 6 detail the baseline results, robustness checks, and additional extensions of the empirical findings. Section 7 concludes.

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[2] Other relevant studies focusing on a narrowed spatial scale: Ahlfeldt et al. (2015) on the land price of before-and-after division Berlin during the World War II, Arzaghi and Henderson (2008) on the location of advertising agencies in Manhattan, Rossi-Hansberg et al. (2010) on the urban revitalization policies in Richmond, Virginia.

[3] In addition, Ohtake et al. (2012) examine the long-term effect of Hanshin earthquake on the labor market by exploiting the data on numbers of job seekers and job vacancies. Ohtake et al. (2014) find the Hanshin earthquake led to a reduction of wage level in quaked areas, the effects proved to be lasting over the 17 years after the occurrence.

2 The Hanshin earthquake

On January 17, 1995, the southern part of Hyogo Prefecture, Japan (Figure 1), was struck by the Hanshin earthquake, which on the seismic intensity scale (based on the Japan Meteorological Agency) was measured as level seven. More specifically, the city of Kobe, 20 km away from the epicenter and with a population of around 1.5 million, suffered maximum damage (Figure 2). Approximately 6,434 people lost their lives (final estimate as of December 22, 2005) in this earthquake, of which about 4,600 were from city of Kobe.[4] Table 1 presents detailed information on the damages and death toll in quaked areas. In addition to Kobe, Osaka, another major city close to the epicenter, was also affected but at a much lower intensity. In most areas of Osaka and its surroundings, the intensity scale was less than five.

After the earthquake, the government proposed a series of policies aiming to recover this city. According to the City of Kobe (2010), the utility in Kobe quickly recovered three months after the earthquake (communication, water, electricity, gas, water, sewage, etc.), and roads and expressways were re-opened in August, 1996. The railways re-opened in January 1996 (with some stations completely destroyed and being reconstructed). As for housing reconstruction, the Kobe City Emergency Three-Year Plan for Housing Reconstruction (EPHR) was formulated, with focus on early recovery from housing loss during the earthquake. This project aimed at providing 82,000 new units of housing by March 1998, and included various policies on rent reduction for public housing (City of Kobe, 2010).

The Hanshin earthquake largely occurred in a super-metropolitan area, a rare case in the recent world history of large-scale destruction. Kobe is the sixth largest city in Japan and one of the three major cities in the Kyoto-Osaka-Kobe MA (Japan's second largest MA, with a population size of 18.8 million in 2005). Thus, the post-Hanshin earthquake Kobe is a novel case study for the long-term impact of natural disasters on major cities with high population density and economic activities.[5]

[4] Kobe City FIRE Bureau (January 17, 2006), Situation of damage and victims: Hanshin-Awaji earthquake (in Japanese): retrieved May 25, 2008.

[5] During the World War II, several major cities were destructed due to bombing, such as Berlin and Hiroshima; however, the urban spatial structure in the 1940s differs from that observed today. The implication from their recovery experience may not apply in current urban development.

3 Theoretical framework

To examine the long-term impact of an earthquake on population dynamics in a MA, I set up a theoretical model incorporating the features of density economies in the service industry and moving cost incurred by residents when migrating within a MA. By doing so, I elucidate the possibility of multiple equilibria in population dynamics.

3.1 Setup

The model is based on a service-dominated multi-city metropolitan area. Before discussing the theoretical setup, I emphasize certain metropolitan and industrial features. Agricultural and manufacturing goods are homogeneous in variety and price within the metropolitan area; thus, they are independent of the comparative location potential of cities within the MA and do not affect the choice of residential location. Moreover, I assume that cities that are considered attractive places to live by residents generally have high location potential for consumers, as implied by the so-called "Consumer City" (Glaeser et al., 2001). In the present model, locational potential refers to the proximity to service consumption, that is, the variety/price of services and distance from them. The model includes two residential small cities (cities 1 and 2) with identical land size, and two major cities (major cities A and B) in the MA. The residents choose to live in one of the small cities on the basis of location potential. The same with the traditional urban models (Fujita and Ogawa, 1982; Fujita, 1989), the CBD (in this metropolitan area case, CBD denotes the major city) is not for residence, but only for service activities.

As Fujita et al. (1999), Glaeser et al. (2001) and Mori et al. (2008) suggest, the hierarchy principle exists in urban systems and industrial distribution. Some industries (called high-order industries) are typically found in major cities, while low-order industries exist in both major and small cities.[6] Therefore, I assume that these two types of services differ in terms of supplier. A low-order service is supplied by small city (e.g., a department store, gymnasium, hospital, restaurant, and etc.), and the variety/price of these services is positively/negatively correlated with the local

[6] Low-order service is also available in major cities, however, as I assume the major city is not for residence, all the demands of low-order service are assumed to be satisfied in residential small city.

population size, which is caused by the density economies in service industry.[7] A high-order service is provided only in major cities, that is, the core cities of a MA (e.g., Kobe, Osaka in Kyoto-Osaka-Kobe MA) and includes large-scale shopping center (e.g., Ginza in Tokyo), entertainment centers (e.g., Disneyland park), museums, aquariums, advanced hospitals, professional expertise on finance and insurance, and etc.

The price and variety of high-order services available in a major city is assumed to be exogenous to small cities 1 and 2 in the model, and accordingly, the proximity to a nearby major city becomes the key factor determining accessibility to these services. Unlike the choice of firm location, which is contingent on good accessibility to all markets, households consider the nearest major city only. I assume that the nearest major city satisfies all demands for high-order services that a local area does not supply (e.g., Osaka, Kobe, and Kyoto are substitutive for consumers living in the Kyoto-Osaka-Kobe MA in terms of high-order services).

Location potential of small cities 1 and 2, thus, depends on three factors: local population size, which determines the availability of variety, as well as the price, of low-order services; distance to the nearest major city, which determines the proximity to high-order services; and urban cost (e.g., congestion, high house price), which increases with population size and restrains single black-hole agglomeration in a small city.

The setup of the model is as follows. Total population in the two small cities is assumed to be constant in the long-term and equal to one. p_1 and p_2 denote the population size of cities 1 and 2 ($p_2 + p_1 = 1$). Locational potential (LP) is a function of p and d (distance to nearest major city):

(1) $$LP = f(p, d).$$

LP decreases with d, suggesting proximity to major city improves the locational potential; LP first increases with p because of the increasing variety and decreasing price of low-order services, and then declines owing to increasing urban costs; the threshold point is set to p^*:

(2) $$\frac{\partial LP}{\partial p} > 0, \text{ if } p < p^*; \ \frac{\partial LP}{\partial p} \leq 0, \text{ if } p \geq p^*; \ \frac{\partial LP}{\partial d} < 0; \ p^* \text{ is subject to } d.$$

To simplify the description on the intuition, I assume the distances to major city for cities 1 and 2 are

[7] Morikawa (2011) finds productivity in personal service industries is positively correlated to population density. Density economies play a much more important role in service industry than in manufacturing industry due to restrictions on the trade of service product. Also, Caves et al. (1984) find traffic density has similar impact on productivity in airlines.

the same initially (denoted as period *a*, pre-earthquake: $d_1^a = d_2^a$). As shown in Figure 3, both the small cities 1 and 2 share the major city A as their nearest major city.

In addition, there exists a moving cost that is a constant equal to *M* for any individual resident migrating from one city to another, which is a type of sunk cost. I assume *LP* can to be measured using a monetary unit, thus differences in *LP* between the two small cities represent the monetary surplus from moving to a city with higher location potential. Residents will migrate from one city to another if the difference in location potential is greater than moving cost: $|\Delta LP| = |LP_2 - LP_1| > M$. Due to the offset of density effect in service industry and urban cost effect, ΔLP firstly increases with p_2 and then decline:

(3) $$\frac{\partial(LP_2 - LP_1)}{\partial p_2} > 0, \text{ if } p_2 < \bar{p}; \quad \frac{\partial(LP_2 - LP_1)}{\partial p_2} \le 0, \text{ if } p_2 \ge \bar{p}; \quad \bar{p} \text{ is subject to } d_1 \text{ and } d_2.$$

At most, there are three level where $LP_1 = LP_2$, which are denoted by the three interaction points of ΔLP function and horizontal line in Figure 4.[8]

3.2 Pre-earthquake steady condition

Initially (in period *a*), I assume the population is decentralized between small cities 1 and 2 (as shown in Figure 4, p_2 drops in the range of equilibria (decentralization)). The difference of locational potential between two small cities is less than *M* and no resident has the incentive to migrate:

(4) $$|\Delta LP^a| = |f(p_2^a,\ d_2^a) - f(p_1^a,\ d_1^a)| < M.$$

3.3 Post-earthquake population dynamics

Due to the large exogenous shock by the earthquake, which destroyed the two small cities and the related major city A. Earthquake damages to the major city lead to a halt in supply by the high-order service industries and a reconstruction recovery. As a result, residents are compelled to look for the second nearest major city for high-order services in period *b* (after the earthquake), and

[8] Note that the partially agglomeration pattern is more stable than that of decentralization (Figure 4). On the one hand, a minor shift beyond the threshold of *p'* will lead to city 2's population continuously moving from *p'* to *p"* (from the decentralization to partially agglomeration condition). On the other hand, for *p"*, once there is a shock shifts p_2 from *p"* towards *p'*, the difference in location potential will automatically lead to a return back of p_2 to *p"*; the only exception is a rather large negative shock to p_2's population, that is, p_2 suddenly drops to less than *p'*. Then, the new steady equilibrium is decentralization.

thus, the distance from the nearest major city for residents in cities 1 and 2 increases. I adopt the following assumption:

(5) $d_1^b - d_2^b >> 0,$

that is, one small city is much closer to the new nearest major city (city B) than the other. Without the loss of generality, I assume city 2 is closer (Figure 3). The difference in *d* in period *b* is much greater than that in period *a* (as I assumed, cities 1 and 2 have the same distance to city A). ΔLP is now obtained by:

(6) $\Delta LP^b = f(p_2, d_2^b) - f(p_1, d_1^b).$

Due to the difference on *d* for two small cities, $\Delta LP^b(0.5, d_1^b, d_2^b) > 0$ (as in Figure 5).

Moreover, earthquake leads to a short-term population loss. The population size of cities 1 and 2 declines (due to those rendered homeless) to αp_1^a and αp_2^a ($0<\alpha<1$) (to simplify the analysis, I assume the degree of destruction is homogenous between cities 1 and 2).Given the assumption in Equation (5), the location potential of city 2 dominates that of city 1shortly after the earthquake:

(7) $f(\alpha p_2^a, d_2^b) > f(\alpha p_1^a, d_1^b).$

Two consequences based on two different channels are expected based on Equation (7):

The location choice of homeless residents whose dwellings were damaged in earthquake. For the homeless residents, counted as $(1-\alpha)(p_1^a + p_2^a)$, when they decide to move back to one of the two cities after seeking temporary shelter in non-quaked areas, they prefer city 2 to 1 because of higher locational potential. Here the magnitude of moving cost *M* is not affecting the locational choice, since house was damaged in the earthquake, thus *M* has already occurred. As a consequence, the population size in city 2 gradually increased to $p_2^a + (1-\alpha)p_1^a$ as the homeless residents return back.

The migration of residents in city 2 whose dwellings were not damaged in earthquake. For the residents of city 1 whose dwellings were not damaged in the earthquake, they have the incentive to migrate to city 2 if $d_1^b - d_2^b$ is sufficiently large, which will straightforwardly induce:

(8) $f(\alpha p_2^a, d_2^b) - f(\alpha p_1^a, d_1^b) > M.$

The intuition is as follows: residents in city 1 choose to migrate to city 2 because city 2 is much closer to major city B, and the utility gain by migration is greater than moving cost M.[9]

In the case that Equation (8) is not satisfied, that is, individual utility gain from the proximity to new major city by migrating from city 1 to city 2 is not great enough to overwhelm the moving cost, I show that density economies in service industry will serve as another channel and also lead to migration. The intuition is as follows: Because of the economies of density in the service industry, the population growth in city 2 by first channel improves the location potential of city 2, and thus, ΔLP^b passes the threshold of M, since the location potential of city 1 does not change with respect to first channel (there is no population inflow, stemming from homeless residents, to city 1 after the earthquake). The intuition is formally expressed as in Equation (9):

$$(9) \qquad f(p_2^a + (1-\alpha)p_1^a,\ d_2^b) - f(\alpha p_1^a,\ d_1^b) > M.^{10}$$

Given the two channels impacting ΔLP^b, the population size of city 2 expands as city 1 shrinks. Migration stops at p_2^b ($\Delta LP^b = M$) when the population dynamics step into the partially agglomeration equilibrium (Figure 5). Residents in both cities 1 and 2 no longer have an incentive to migration.

3.4 Reconstruction of the quaked major city

In the case of the Hanshin earthquake, the damaged city of Kobe rapidly recovered its infrastructural facilities after the earthquake: in the first three years after the quake, a number of new dwellings were built in the quaked area (Figure 6) and financial aid (reconstruction funds) from the central government was intensive (Figure 7). This suggests that after the first few years, short-term intensive reconstruction was complete and urban functioning partially recovered, although the long-term recovery continued in the following decades.

After the short-term intensive recovery, Kobe resumed as a core city in the metropolitan area. However, even if the reconstruction was complete, (d_1, d_2) for small residential cities 1 and 2 returns from (d_1^b, d_2^b) to (d_1^a, d_2^a), the new residents in city 2 still do not have the incentive to return to city 1. Perhaps, in the case that the post-quake migration from city 1 to city 2 is still ongoing when the

[9] If moving cost M is sufficiently large, then in all cases, the locational potential difference is less than M, and as a result, any distribution is in equilibrium. If $M = 0$, then only the three points with identical LP between the cities 1 and 2 are in equilibrium (the decentralization equilibrium is rather unstable, a minor shock to the population will lead to another state of equilibrium).

[10] I assume $p_2^a + (1-\alpha)\ p_1^a < p^*$, that is, during the population inflow to city 2 from p_2^a to $p_2^a + (1-\alpha)\ p_1^a < p^*$, the positive effect of density economies (service industry) on LP dominates the negative effect of urban congestion on LP.

reconstruction of major city is complete, then the population loss of city 1 continues even after the reconstruction, and stops at *p"* (Figure 4). Partially agglomeration in city 2 steps into a steady state, which significantly differs from the initial pre-quake equilibrium (i.e., decentralization). The distribution will return to the decentralization pattern only if there is another exogenous shock greatly expands the population size of city 1, but makes city 2 shrink to less than *p'*.

3.5 Applying the model to the Hanshin earthquake

As per the model, the earthquake leads to a population loss in all the quaked areas; however, the location potential is not homogeneously affected, even if the degree of shock to the population is the same, given the differing distance to the new nearest major city. In addition to Kobe, Osaka, another major city close to the quaked areas, was not significantly affected in the Hanshin earthquake. I assume that the quaked areas closer to Osaka gain an extra comparative advantage in location potential compared with other damaged areas. In particular, in line with the model's setup, Kobe is seen as the initial pre-quake nearest major city (city A), whereas Osaka is the next nearest one and less affected by the earthquake (city B), replacing the role of Kobe. *One-third of Kobe's shopping districts and one-half of its markets were heavily damaged during the Hanshin earthquake (City of Kobe 2011), this suggests the city of Kobe was not a qualified place after the earthquake which provides the high-hierarchy service products.* I conduct the following empirical analysis to test the channels and conclusions derived from the model.

4 Empirical strategies

Given that the earthquake was unexpected, and thus clearly exogenous, I compare the gradual patterns in the residential population of areas exposed to the Hanshin earthquake with those of control areas in the unaffected regions. To construct a credible control group, I adopt the synthetic control approach for a comparative analysis to overcome two main problems: the pre-earthquake trend of population growth and an insufficient sample size.

First, I assume in the model that the total population is constant for the two residential cities before the quake; however, this is not the case in a real metropolitan area. There are several factors determining the population size of a metropolitan area, for example, natural growth, rural-urban and inter-city migration. To test the impact of the earthquake, it is necessary to control for the initial trend of population dynamics caused by other factors.

Second, unlike the difference-in-difference estimates, the synthetic control approach does not always require a large sample size for treated and control units. To evaluate the impact of natural disasters, general regressions do not warrant a large sample size in the case of a local event. Second, in the case of more than one treated units, the treatment impact of each unit is separately estimated in the synthetic control approach, which allows us to observe the heterogeneous impact. As suggested in Barone and Mocetti (2014) and Ando (2015), given the similar scale and timing of treatment, there is significant within-country heterogeneity in the treatment effects of units. In this case, a difference-in-difference approach may omit such heterogeneities when estimating the treatment's average effect. In addition, for robustness checks, I combine the synthetic control approach and regressions on population dynamics to account for a series of additional control variables.

4.1 Synthetic control approach and sample selection

The synthetic control approach was developed by Abadie and Gardeazabal (2003) and Abadie et al. (2010), and was later adopted by Cavallo et al. (2013), Barone and Mocetti (2014), Ando (2015) and et al. The approach aims at constructing a counterfactual unit of a treated unit using the weighted average of a set of controls, after which the outcomes of the treated and counterfactual unit are compared to evaluate the treatment impact. To construct a highly comparable synthetic control, the weighted average of outcome variables, as well as the relevant covariates, of the control units in the pre-treatment periods should be as close as possible to those of a treated one.

For the sample selection of the synthetic control, I focus on the urban areas mainly damaged the Hanshin earthquake at the municipality level. Although Awaji Island (classified as a rural area in the study period) also suffered an earthquake measuring seven on the seismic intensity scale, I exclude it from analysis since its population density is much lower than that in the damaged areas around Kobe.

Municipalities located in a metropolitan area tend to have different population dynamics with general peripheral municipalities, since they are more affected by the expansion of major cities. To be comparable with the treated samples which are located in Kyoto-Osaka-Kobe MA, I choose donor municipalities located also in (or close to) a large-scale metropolitan area. According to *Seirei Shitei Toshi* (in Japanese), there were 13 designated cities before 2003, which are the largest cities in Japan (Table 2), among which Kobe was the sixth largest in 2000. The population dynamics for these cities are diverse: cities in Tokyo MA (Tokyo[11], Yokohama, Chiba, and Kawasaki) experienced significant population growth in the past three decades; cities in northern Japan, such as Sapporo and Sendai, also show a strong tendency of population growth; other major cities in southern Japan, including Nagoya, Osaka, Kyoto, and Kobe, do not report much growth. Only in Fukuoka, the population increased by more than 20%.

I first base the donors for constructing the synthetic control on the samples of major metropolitan areas in the southern Japan, because they depict similar geographic location and the population dynamics are comparable within the study period. Of the seven designated cities in the south of Japan, Kobe and Osaka are taken as treated cities and Nagoya, Kyoto, Kitakyushu, Fukuoka, and Hiroshima are donor cities. The overall growth tendency in the five donor cities is higher than that in Kobe, but lower than those in Nagoya, Kitakyushu, and Kyoto. However, this difference is not large compared with the other designated cities. The population size is also comparable for 1990: the largest city in the control group is Nagoya (2.15 million) and the smallest is Kitakyushu (1.02 million) followed by Kobe (1.47 million).

As for the urban area in Japan, there are two municipality-level administrative units: city and district. The designated cities comprise several municipality-level districts. For instance, Kobe consists of nine municipality-level districts, which is much larger in size than the general municipality-level cities. For treated districts in Kobe, I choose the donors for constructing synthetic control from districts in the southern Japan designated cities, namely, Kyoto, Nagoya, Fukuoka, Kitakyushu, and Hiroshima. These five major cities are involved in four prefectures: KYOTO, AICHI, FUKUOKA, and HIROSHIMA, the municipality-level cities in these four prefectures are thus selected as the donors for quaked municipality-level cities (Table 3). Municipality-level cities in both treated and donor samples are close to a major city, they are thus supposed to be comparable on population growth.

[11] To avoid confusion on the geographical scale, throughout this paper, Tokyo refers to the city of Tokyo which includes 23 municipality-level districts, and TOKYO refers to as Tokyo prefecture, it includes 23 municipality-level districts (city of Tokyo) as well as 27 municipality-level cities and 13 municipality-level towns or villages (as per the administrative division in 1990). This also holds for Osaka/OSAKA, Kyoto/KYOTO, Fukuoka/FUKUOKA, Hiroshima/HIROSHIMA, China/CHIBA, and Saitama/SAITAMA.

I analyze the population dynamics before and after the earthquake for 1988–2003, since the population data for the municipalities are available in this period. After 2003, a number of donor municipalities were merged, and thus, the population size could no longer be compared.[12]

At the municipality level, I choose the treated units as quaked urban areas (cities and districts) in which the earthquake intensity was no less than five: 17 municipalities in HYOGO and five in OSAKA (Yodogawa municipality was excluded owing to insufficient population data) (Figure 8).[13] There are 22 treated municipalities, of which 11 are districts and the remaining 11 are cities. As for donors, there are 47 municipality-level districts and 70 municipality-level cities (Table 3). Following Abadie et al. (2010), for each treated municipality-level district/city, there are 47/70 donor municipalities.

4.2 The application of synthetic control approach

The application of synthetic control approach for districts and cities are analogous but with different donor groups. Hereinafter, I only discuss the case for districts. Let $p_{it}{}^{1}$ be the potential population in municipality-level district i (i = 1, …, 48)[14] at time t (t = 1988,…, 2003) if the district is hit by the earthquake and $p_{it}{}^{0}$ if the district is unexposed to the quake. There is no earthquake impact on the population before the earthquake (i.e., no expectation on earthquake), so $p_{it}{}^{0} = p_{it}{}^{1}$ for the years before 1995.

Without loss of generality, I assume that the first district is the treated one and the rest 47 are donors. Let $\alpha_{1t} = p_{1t}{}^{1} - p_{1t}{}^{0}$ (t > 1994) be the effect of the earthquake in 1995. Let D_t be a dummy variable equal to 1 for years post the earthquake, and 0 otherwise. Then, the observed population in the quaked district can be written as:

(10) $$p_{1t} = p_{1t}{}^{0} + \alpha_t D_t .$$

[12] During 2003–2006, the number of municipalities in Japan reduced from 3212 to 1821 (Yodomichi, 2007). The quaked area was not affected by the merger, while a number of donor municipalities were merged.

[13] I aggregated the earthquake intensity observations within a municipality: if more than half the intensity scale observations were no less than five, then I took it as a treated municipality. Based on the classification of Japan Meteorological Agency (JMA) seismic intensity scale, intensity scale of five means the earthquake is strong enough to make both the wooden structure houses and reinforced concrete frame houses appear cracks.

[14] For each treated municipality-level district, there are 47 control municipality-level districts.

For the quaked district, p_{it}^{0} is not observable for the years after the earthquake and needs to be estimated. Following Abadie et al. (2010), I estimate α_t as $\alpha_t = p_{1t} - \sum_{j=2}^{48} w_j p_{jt}$ for the years after the earthquake, where weights w_j are chosen by minimizing the Mean Squared Prediction Error (MSPE) (Abadie et al., 2010) that depends on the population dynamics before the treatment, as well as the pre-treatment values of predictors of population growth.

The key outcome of interest is the population index (population in 1994 = 1). The population index predictors are the population index for 1988–1994, population index at the prefecture level (prefecture in which the sample municipality located) for 1988–1994 (1994 = 1), population size in 1994, land area, employment structure (employment share of the service sector in total employment) in 1991, aging rate in 1990, total number of firm in 1991, and residential land price in 1993 (I include only one-year data for some predictors partly due to the limitation on data availability; Table 4 presents the data summary). MSPE is minimized over 1988–1994 for all the exercises. I conduct 22 independent exercises for 22 treated municipalities to construct 22 synthetic controls.

5 Empirical findings

In this section I firstly present the results for the synthetic control approach and discuss the population dynamics as per graphical evidences. Then, I conduct regressions combined with the results of the synthetic control approach and additional control variables to provide robustness checks in terms of confounded factors.

5.1 Evidences from synthetic control approach

Figure A.1 presents the raw results of the synthetic control approach for each sample municipality. I find that the pre-earthquake pattern of population growth between sampled units and their synthetic control units are generally adjusted and controlled with high similarity. By contrast, the post-earthquake trend is diverse. For some municipalities, the post-earthquake population dynamics do not significantly differ among synthetic control units (e.g., Itami and Ikeda), whereas some experienced a significant drop after the earthquake (e.g., Akashi and Nagata) and some others enjoyed higher population growth than the control units (e.g., Takrazuka and Kawanishi). In addition, one group reported interesting results: for the first few years after the quake, there was a significant population drop; however, they quickly recovered and gained additional surplus compared with the synthetic control units (e.g., Ashiya and Nishinomiya).

However, by dividing them into three groups on the basis of the distance to Osaka, the pattern becomes clear. For the quaked municipalities in OSAKA, their population indexes are either unaffected or increasing, but not decreasing ((a) in Figure A.2). The sample municipalities in the east side of Hyogo suffered more severe damage than the quaked areas in Osaka, and thus, its population level was the first to drop. However, as shown in (b) in Figure A.2, most of the population levels in these areas quickly recovered and even exceeded that of the initial growth path. In 2003, almost all the municipalities (except Amagasaki) had a higher population index than the case without the earthquake, even if most of them experienced significant population loss in 1995–1997. For the third treated group in the west side of Hyogo, the samples for which included areas most distant from Osaka, the population decreased ((c) in Figure A.2).[15] Only the population in Nishi increased compared those to the synthetic control, however, as shown in (c) of Figure A.2, the pre-earthquake population index trend for Nishi was not sufficiently comparable to the synthetic control units and thus, it should be treated as an outlier.

Graphically, the pattern of population growth in the quaked municipalities is correlated with the distance to Osaka. The population in municipalities further away from Osaka experienced a decline in population after the earthquake, while that in municipalities closer to Osaka increased.

5.2 Varying trends in comparison with synthetic control

In this section, I analyze the population dynamics using aggregated data to identify, first, whether the total population in the quaked areas recovered from the earthquake, and second, if the pattern of population growth shown in Section 5.1 remains statistically significant. I use only data for

[15] The weights and MSPE for each exercise can be made available upon request. Similar to most of the literature on the synthetic control approach (e.g., Abadie et al., 2010; Ando, 2015), placebo tests were conducted using the donor as the counterfactual treated unit (Table A.3). I present two placebo tests for Nishinomiya (east side of Hyogo) and Suma (west side of Hyogo). The magnitude of treatment effects for 2003 is dropped in the upper/bottom 5% for Nishinomiya and Suma, suggesting that the results are statistically significant (Nishinomiya ranks 2nd among 71 and Suma ranks 47 among 48, that is, Nishinomiya has a significantly higher population growth than the controls, while Suma has a significantly higher population loss than the controls.). Not all the results are statistically significant to the placebo tests; nevertheless, the pattern is convincing (Tables A.1 and A.2).

the 17 sample municipalities in HYOGO (eight in west side and nine in the east) because they belong to the same prefecture, and the five quaked municipalities in OSAKA were less affected than the damaged areas in HYOGO. As shown in (a) of Figure A.2, the five quaked municipalities in OSAKA actually reached higher population growth in 1995–2003 than the synthetic control units.

By replacing the population index of the synthetic control for 1995–2003 with the related treated unit, I calculate the counterfactual population of the sample municipality without the earthquake.[16] As mentioned in Section 4.1, the population data before and after 2003 are not sufficiently comparable due to municipality mergers. Thus, I conclude the estimates of the synthetic control in 2003. Alternatively, I present the linear trend of population for 2004–2011 on the basis of the population index for 1988–1994, and the counterfactual population in the synthetic control units for 1995–2003.[17]

As shown in the left-hand side (LHS) of Figure 9, the total population in the 17 quaked municipalities of HYOGO gradually increased by 2.4% during 1988–1994, which is slightly higher than the national population growth at the time (2.0%). More specifically, as presented in the right-hand side (RHS) of Figure 9, the population in the east side (nine municipalities, which are relatively close to Osaka) declined by 0.7%, whereas that in the west side (eight municipalities) rapidly increased by 6.7%, suggesting the pre-quake trend on population dynamics is different among quaked areas.

On the post-quake condition of recovery, I find that in 2009, the total population fully recovered compared with the case without the earthquake (i.e., pop_2009/pop_trend_2009≥1.0), although it decreased by 2.0% in the first two years after the quake. For the east areas, it initially dropped by 3.6% but quickly recovered in 2000 (i.e., pop_2000/pop_trend_2000≥1.0) (RHS of Figure 9), after which it exceeded the initial population growth path. For the west, the population growth was consistently lower than that of the control in 1995–2011. Compared to the synthetic control, it suffered a 10.4%[18] loss in 2011 because of the earthquake, while the east areas saw an 8.3% growth (Figure 10). The population growth trends in two areas are not likely to alter by 2011, suggesting the population loss

[16] The counterfactual population of a treated municipality in 2003 is calculated based on its population size in 1994 and related population index of synthetic control unit in 2003, as pop_counterfactual=pop_1994*popindex_synth_2003.

[17] The counterfactual population of a treated municipality for 2004–2011 is predicted by the linear trend of population in 1988–1994 and counterfactual population in 1995–2003.

[18] It is calculated based on the population in 2011, predicted counterfactual population in 2011, and population in 1994, as follows: (-(pop_2011-pop_trend_2011)/pop_1994)*100%.

in west areas tends to be lasting. Based on the theoretical model, the post-quake migration from city 1 to city 2 will continue until the partially agglomeration in city 2 enters a steady condition, even if reconstruction in the damaged major city is complete.

In sum, the population in the west areas of the quaked municipalities showed an increasing trend before the Hanshin quake, while the east areas stagnated. However, 16 years after the earthquake, the population dynamics significantly changed: the east areas (once stagnated) dominated the west areas in population growth. As shown in Figure 9, the time node for this pattern shift was around 1995, which is presumably around the time of the earthquake.

Figure 11 further elucidates if the damage to Kobe and proximity to Osaka affects the altered population dynamics, as discussed in the model. As shown on the LHS of Figure 11, the population growth during 1994–2003 for the sample municipalities is not significantly related with the distance to Osaka. However, considering the growth pattern in the synthetic controls, and accounting for the difference in the population index between the treated and synthetic control units, the RHS of the graph shows a significant downward slope to the distance to Osaka. That is, by excluding the impact by the pre-earthquake population growth trend, the post-earthquake population growth becomes significantly related to the distance to Osaka.

The pattern shown on the RHS of Figure 11, clearly, is not the direct consequence of damage by the earthquake, since the areas that did not experience significant damage also experienced considerable population loss (e.g., Miki and Akashi), and the municipalities extensively destroyed but close to Osaka showed significant growth (e.g., Suida and Kawanishi) (Related confounded factors are formally controlled in regressions of Section 5.3). This may be in line with the opinion initially presented in the model: the destruction of Kobe decreases the *relative* location potential of municipalities in the west of Kobe, but increases that of municipalities in the east side of Kobe (close to Osaka).

5.3 Regressions of the first difference with synthetic control units

Before concluding that multiple equilibria is a major channel in residential location, it remains necessary to exclude two potential confounded factors inducing the results in Figure 11: the probability of a strong earthquake in the future and the degree of destruction by the Hanshin earthquake. The two factors also affect population dynamics in the quaked areas. In this section, by taking the first difference of the population index with the synthetic control units, I conduct regressions on the distance to Osaka to examine the impact of the confounded factors.

First, as suggested in theory by Scawthorn (1982), given the possible awareness of a natural hazard within an urban area, a residential location is generally selected on the basis of its proximity to high risk areas. Relevant empirical evidences are shown in Nakagawa et al. (2007) and Naoi et al. (2009). Given the advancement on earthquake prediction, the possibility of an earthquake in the near future tends to affect residential location choice. To examine whether this possibility induces the results shown in Figure 11, I conduct a regression as follows with the municipality-level data for 1988–2003:

$$(11) \qquad \Delta PopG_{it} = \alpha_1 y9597_t \cdot Dist_i + \alpha_2 y9803_t \cdot Dist_i + \alpha_3 y9597_t \cdot C_i + \alpha_4 y9803_t \cdot C_i + \delta_i + \mu_t + \varepsilon_{it}.$$

The dependent variable is the first difference of annual population growth rate between treated units and synthetic control units. On the independent variables, I insert interaction terms between the time dummy and distance (km) to core Osaka (*Dist*). There are two time dummies: *y*9597 (which takes that value of 1 for 1995–1997, and 0 otherwise) and *y*9803 (which takes that value of 1 for 1998–2003, and 0 otherwise). The two time dummies separately capture the short- (migration due to homelessness) and long-term impact (migration due to location potential preference). To consider the factors mentioned in the previous paragraph, I also insert interaction terms of dummy variables and additional controls C_i: the possibility of an earthquake, and the degree of earthquake destruction in 1995. Municipality and year fixed effects are controlled for by δ_i and μ_t.

Thus, α_2 is the key coefficient and measures the pattern of population growth in terms of distance to Osaka and it is expected to be significantly negative. Since α_1 is mixed with the temporary population loss due to shelter seeking by the homeless, it is not necessary for it to be related to the distance to Osaka, and thus, the sign is expected to be undetermined.

Column 1 of Table 5 provides the baseline results for the 17 quaked municipalities in HYOGO, without controlling for the possibility of a quake. α_2 is significantly negative at -0.06, suggesting that the annual population growth would decline by 0.06 percent if the distance to Osaka increased by 1 km. Then, in column 2, I include also the five quaked municipalities in OSAKA. The coefficient is smaller at -0.04, but significant at the 5% level. In column 3 of Table 5, I consider the possibility of a strong earthquake (≧6 on the intensity scale) for 2005–2035.[19] By doing so, I find that the results remain unchanged and quake possibility does not have significant impact on population growth. Column 4 estimates the impact of the degree of destruction by the Hanshin earthquake on the following population dynamics. I insert the degree of house destruction in 1995 for each sample municipality (I include only the 17 municipalities in HYOGO owing to missing municipality-level destruction data for OSAKA.). For the first three years, there is a significant relationship between destruction degree and population loss, that is, municipalities that were severely damaged experienced a higher degree of population loss. By contrast, in 1998–2003, there is a positive significant relationship between the degree of house destruction in 1995 and population growth, suggesting the seriously damaged areas gradually recovered, however, the pattern in terms of distance to Osaka remains significant at -0.05.

5.4 Regressions using samples in Kyoto-Osaka-Kobe MA

Here, I question whether agglomerating with core Osaka was a trend in all municipalities in the Kyoto-Osaka-Kobe MA during 1995–2003. In this case, the estimates appear to be primarily driven by this trend rather than the impact of the earthquake. Some estimates are conducted using the unaffected cities in the Kyoto-Osaka-Kobe MA as the control. In doing so, the factor of overall trend impacting the baseline results is addressed.

As shown in Figure 12, Osaka is located in the geographical center of the Kyoto-Osaka-Kobe MA (Broadly, it consists of five prefectures: OSAKA, KYOTO, HYOGO, NARA, and WAKAYAMA.), with Kobe on the west side and Kyoto in the northeast. Sakai, located to the south of Osaka, is also a major city in the Kyoto-Osaka-Kobe MA, which was upgraded to a designated city in 2006 (population size was 0.83 million in 2006). By comparing the population dynamics in the Osaka-Kyoto area, Osaka-Sakai-Wakayama area, and Osaka-Nara area (Figure 12) with the population growth in the quaked areas along Osaka-Kobe area, I capture whether the other areas in the Kyoto-Osaka-Kobe MA show a tendency to agglomerate with Osaka. Thus, I perform the

[19] Data on the possibility of a strong earthquake are only available for the period of 2005–2035. Since 1995, there has been no massive quake in the Kyoto-Osaka-Kobe MA. I assume the long-term probability of a strong quake is stable in the Kyoto-Osaka-Kobe MA between 1995 and 2005.

estimation as Equation (12) considering the distance to Osaka, a post-earthquake dummy for time period, and a dummy for quaked areas:

$$(12) \quad \begin{aligned} PopG_{it} &= \alpha_1 Q_i \cdot y9597_t \cdot Dist_i + \alpha_2 Q_i \cdot y9803_t \cdot Dist_i + \alpha_3 Q_i \cdot y9597_t + \alpha_4 Q_i \cdot y9803_t \\ &+ \alpha_5 y9597_t \cdot Dist_i + \alpha_6 y9803_t \cdot Dist_i + \delta_i + \mu_t + \varepsilon_{it}. \end{aligned}$$

$PopG_{it}$ is the annual rate of population growth for municipality i and year t. Q is a dummy that distinguishes between treated and control samples. For the treated samples, I include the 20 quaked municipalities (17 municipalities in HYOGO and three municipality-level cities in OSAKA. Two quaked municipality-level districts in Osaka are excluded from the estimate because population of Osaka is confounded, as it is correlated to the population dynamics of both the treated and control samples. Control samples include the municipalities in the four prefectures' urban area: OSAKA (except Osaka), KYOTO, WAKAYAMA, and NARA. In total, there are 64 control municipalities. Table 6 presents the data summary.

*y*9597, *y*9803, and *Dist*, as well as the municipality and year fixed effects, are identical with those in Section 5.3. Thus, α_2 is the key coefficient. If the population dynamics pattern (Figure 11) is not driven by the agglomeration trend in the Kyoto-Osaka-Kobe MA, then α_2 is expected to be negative, that is, in comparison to the other municipalities in the Kyoto-Osaka-Kobe MA, the quaked municipalities show a significantly higher gradient of population growth in terms of proximity to core Osaka.

Figure A.4 presents the population growth for control municipalities in 1994−2003 by the distance to core Osaka (the trend of population growth in 1988−1994 is removed). Unlike the trend in treated group, there is no significant downward sloping on the fitted line of control group. Column 1 of Table 7 provides the relevant estimates. α_2 is significantly negative at -0.07 and α_4 is significantly positive at 2.46, suggesting quaked municipalities within 35 km (≈2.46/0.07) to core Osaka reach higher population growth than the control in 1998−2003 while the rest quaked areas suffer from population loss in this period. The estimated threshold of distance (i.e., 35 km) is highly consistent with the graphical evidence in the RHS of Figure 11, although I use alternative control samples. Column 2 presents the results by controlling for prefecture-year and municipality fixed effects, which clears out the disturbance from the prefecture-year level macro shock. α_2 is still significant at -0.09. In column 3, I include only the overlapped distance samples to ensure treated and control samples drop in the same distance range on the proximity to core Osaka, the result is almost unchanged. Column 4 provides the difference-in-difference estimates, not accounting for distance to Osaka. For 1995–1997, the population growth in treated samples is significantly lower than the control, but for 1998–2003, the difference is not significant. Finally, in column 5, I control for the possibility of a strong earthquake in the near future and the result is consistent with the baseline estimates.

Table 7 provides evidence that the gradient of the population dynamics in terms of distance to Osaka is not driven by the overall agglomeration pattern in the Kyoto-Osaka-Kobe MA. The estimates do not overturn the implication from the theoretical model and synthetic control approach (Figures 9–11).

6 Further discussion

6.1 Cross-prefecture employment

One additional possibility of rapid growth in the east areas of Kobe is the expansion of Osaka. More specifically, this refers to the increased employment demand in OSAKA by residents in the east areas of HYOGO, since the commuting time between core Osaka and core Kobe is less than 30 minutes by rail.

However, data shown in Figure 13 suggest the contrary. Although the cross-prefecture employment in the east side of the quaked areas of HYOGO is high among the share of total residents (15%), the ratio did not increase after the earthquake. By 2000, the east area's population had already recovered to the pre-quake condition. However, the cross-prefecture employment remained significantly lower than that before the quake (1990). Assuming the average employment-to-population ratio is relatively stable within this short period (50.6% in 1990 and 50.8% in 2000, Japan Statistical Yearbook), the hypothesis that the rapid population growth in the east side of quaked HYOGO can be attributed to the inward flow of Osaka's commuting population is partially rejected.

6.2 Land price

It’s desirable to test directly the post-quake evolution of service industries with respect to density economies, by which I may examine the reliability of the channel implied by the theoretical model. However, municipality-level data on the productivity or output of service industry, by which density economies is measured, are not readily available.

I utilize the land price to provide additional evidences concerning on the channel of post-quake population migration. First, growth rate of residential land price is taken as a proxy of change on the locational potential, municipalities with increasing (relatively) locational potential tend to have high growth rate on residential land price. Second, growth of commercial land price is supposed to be in parallel with an increase in productivity/output of local service sector, that is, municipalities enjoy high density economies in service industries are expected to reach high productivity, leading a raise on local commercial land price.

Residential and commercial land price data are available since 1993; thus, we have data for two years before the earthquake. Table 8 presents the results obtained using the distance measure within the Osaka-Kobe-Kyoto MA, which are consistent with the estimates for residential population (Table 7).

I first estimate the impact of the earthquake on residential land price. Column 1 of Table 8 suggests that the residential land market in treated areas have similar growth pattern with residential population size. Result is robust when the overlapped distance is accounted for (column 2).

In addition, because of the burst of the economic bubble at the beginning of the 1990s, residential land price dramatically dropped, especially in metropolitan areas. Since major cities have a much higher land price, I separately estimated the impact for municipality-level districts (i.e., Kobe) and municipality-level cities (i.e., other quaked areas except Kobe). I find there is a significant difference on the magnitude of estimated coefficients between district samples and city samples, however, the pattern is similar. Then, column 5 presents the estimates for commercial land price, results come to be similar with that of residential land price, suggesting the municipality performance in service industries (implied by the dynamics of commercial land price) tends to be associated with the proximity to Osaka in 1998–2003.

7 Conclusions

In this study, I examined the long-term consequence of Hanshin earthquake on urban spatial structure by synthetic control approach. The results revealed that, first, the natural disaster does not have persistent impact on the total population of quaked areas. Second, the internal residential distribution significantly changed, that is, the population tended to agglomerate toward the less affected major city, Osaka, given the serious damage in Kobe. I identified multiple equilibria as the determinants of this population dynamics.

This multiple equilibria is rooted in the tradeoff between residents' moving cost for residential location and demands for service product. The findings of this study have implications for other major cities at a high risk of natural disasters as well as those engaged in formulating big-push policies.

Despite this study providing empirical evidence on multiple equilibria in residential location, it is subject to certain shortcomings. This study largely assumed the importance of moving cost of within-metropolitan migration; however, given that numerous residents do not purchase land property, but only rent apartments, the moving cost is not as high. Moreover, land property influences the populations' decision to return to their initial residential location after a large-scale destruction (See Davis and Weinstein (2002) on the bombings in Japan); however, this was not discussed in this research owing to the lack of data. duPont and Noy (2015) discuss the long-term consequences of Hanshin earthquake at the aggregate level (Hyogo prefecture) by testing various indicators (population, GDP per capita, government expenditures, etc.), while this paper focuses only on the population dynamics due to data limitations.

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Table 1: Direct consequences of the Hanshin earthquake

	Municipality	Number of houses destroyed	Number of houses destroyed /Pop_1994 (%)	Area destroyed by fire (m^2)	Area destroyed by fire /Land area (%)	Deaths (person)	Deaths /Pop_1994 (%)
Districts of Kobe	Higashinada	10,800	5.8	39,215	0.1	1,216	0.7
	Nada	9,220	7.6	27,600	0.1	819	0.7
	Hyogo	4,373	3.7	12,420	0.1	403	0.3
	Nagata	15,994	12.8	503,350	4.4	712	0.6
	Suma	7,811	4.2	305,600	1.1	333	0.2
	Chuo	6,544	6.4	21,700	0.1	206	0.2
	Tarumi	193	0.1	50	0.0	2	0.0
	Kita	2	0.0	60	0.0	8	0.0
	Nishi	0	0.0	70	0.0	3	0.0
Cities close to Kobe	Amagasaki	1,478	0.3	3,372	0.0	27	0.0
	Akashi	535	0.2	100	0.0	5	0.0
	Nishinomiya	13,931	3.4	9,600	0.0	938	0.2
	Ashiya	4,062	4.8	5,600	0.0	405	0.5
	Itami	887	0.5	295	0.0	10	0.0
	Takarazuka	5,057	2.5	148	0.0	86	0.0
	Miki	138	0.2	13	0.0	2	0.0
	Kawanishi	1,523	1.1	0	0.0	1	0.0
OSAKA	#Osaka pref.	2,342	0.0	2,310	0.0	14	0.0

Notes: Data are from Edgington (2010). Municipality-level data on earthquake consequences are not available for Osaka prefecture, data recorded are the aggregated values at the prefecture level.

Table 2: Population dynamics in Japan's major cities

Region	City	1985	1990	1995	2000	2005	2010	2014	Growth(%): 1985–2014
Northern Japan	Sapporo	1.54	1.67	1.75	1.80	1.88	1.91	1.93	25.3
	Sendai	0.70	0.91	0.97	1.01	1.02	1.05	1.05	50.0
Tokyo MA	Tokyo	8.35	8.10	7.94	8.09	8.35	8.95	9.02	8.0
	Yokohama	2.99	3.20	3.30	3.41	3.55	3.67	3.71	24.1
	Kawasaki	1.09	1.17	1.20	1.25	1.33	1.43	1.43	31.2
	Chiba	0.79	0.82	0.86	0.88	0.92	0.96	0.96	21.5
Southern Japan	Nagoya	2.11	2.15	2.14	2.15	2.19	2.26	2.25	6.6
	Osaka	2.63	2.60	2.60	2.60	2.59	2.67	2.67	1.5
	Kyoto	1.48	1.45	1.45	1.45	1.46	1.47	1.42	-4.1
	Kobe	1.41	1.47	1.42	1.49	1.52	1.54	1.55	9.9
	Hiroshima	1.04	1.08	1.11	1.12	1.14	1.17	1.19	14.4
	Fukuoka	1.16	1.23	1.28	1.34	1.38	1.46	1.47	26.7
	Kitakyushu	1.06	1.02	1.02	1.01	0.99	0.98	0.98	-7.5
National total		121.05	123.61	125.57	126.93	127.77	128.06	126.95	4.9

Notes: Population in million. Data for 1985–2005 are from Japan Statistics Bureau: Historical Statistics of Japan-Population of Major Cities: http://www.stat.go.jp/english/data/chouki/02.htm. Data for 2010 are from the Japan Statistical Yearbook, 2013. Data for 2014 are from Japan Statistical Yearbook, 2015. Before 2003, there were 13 designated cities (*Seirei Shitei Toshi*; in Japanese) as shown in the table. These are the largest cities in the country.

Table 3: Treated and donor units

Treated units (Sample size)	Donor units (Sample size)
Municipality-level districts in Kobe and Osaka (11)	Municipality-level districts in Kyoto, Nagoya, Fukuoka, Kitakyushu, and Hiroshima (47)
Municipality-level cities in quaked area (11)	Municipality-level cities in KYOTO, AICHI, FUKUOKA, and HIROSHIMA (70)

Table 4: Data summary for synthetic control approach

Number of sample municipalities		Treated units 22	Synthetic control units 22	Donor units (Average of the control units) 117
Indicator	Year	Mean	Mean	Mean
Pop. index (1994=1.00)	1988–1994	1.00	1.00	0.99
Pref_Pop. index (1994=1.00)	1988–1994	0.99	0.99	0.99
Population	1994	196,638	152,263	113,500
Land area (km^2)	1994	53.38	67.74	78.51
Service employment share	1991	0.71	0.72	0.65
Aging index	1990	0.15	0.17	0.17
Firm number	1991	9,541	8,685	6,563
Residential land price (JPY/m^2)	1993	328,535	239,038	162,532

Notes: Some data were taken for the fiscal year, which runs in Japan from April 1st, therefore, the earthquake (January, 1995) was recorded as happened in the fiscal year of 1994. For such cases, I set the data of fiscal year 1994 as the data for 1995. Aging index: population aged 65 and over / total population. Data for land prices are missing for municipalities in OSAKA; thus, the number of treated and synthetic control units is reduced to 17 (Land price was excluded from the predictors for the synthetic control approach for the five treated samples in OSAKA). By minimizing the MSPE, 43 out of 117 donor units are selected as the basis to construct the 22 synthetic control units.

Table 5: Population dynamic compared with synthetic control units

	(1)	(2)	(3)	(4)
	Δ Annual rate of population growth (first difference with synthetic control units) (expressed as a percentage)			
y9597*Dist	0.006	-0.016	-0.008	-0.008
	(0.018)	(0.015)	(0.018)	(0.011)
y9803*Dist	-0.060**	-0.040**	-0.044**	-0.050*
	(0.030)	(0.020)	(0.020)	(0.026)
y9597*quake_prob.			0.301	
			(0.534)	
y9803*quake_prob.			-0.171	
			(0.394)	
y9597*houses_dest.p.c.				-32.397***
				(4.084)
y9803*houses_dest.p.c.				21.292*
				(11.138)
Constant	1.770*	0.532	1.587	0.798
	(0.963)	(0.398)	(1.129)	(0.877)
Municipality fixed effect	Y	Y	Y	Y
Year fixed effect	Y	Y	Y	Y
No. of treated municipalities	17	22	22	17
Sample area	HYOGO	HYOGO&OSAKA	HYOGO&OSAKA	HYOGO
N	272	352	352	272
R^2	0.243	0.177	0.181	0.453

Notes: Time period is 1988–2003. Robust standard errors are in parentheses (clustered at the municipality level)
* $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$.

Table 6: Data summary for estimates with Kyoto-Osaka-Kobe MA as control

		Treated		Control	
Number of sample municipality		20		64	
Indicator	Year	Mean	S.D.	Mean	S.D.
Annual growth on residential population (in percentage)	1988–1994	0.33	1.91	0.15	1.38
	1995–1997	-0.73	2.59	0.36	0.93
	1998–2003	0.49	1.02	-0.05	0.61
Annual growth on residential land price (in percentage)	1993–1994	-9.95	7.99	-6.04	5.45
	1995–1997	-2.65	2.58	-2.36	1.91
	1998–2003	-7.11	3.48	-5.94	3.13
Annual growth on commercial land price (in percentage)	1993–1994	-17.01	7.30	-13.11	9.20
	1995–1997	-9.06	5.68	-8.49	4.83
	1998–2003	-9.83	3.42	-9.34	3.16
Distance to core Osaka (km)		28.57	13.7	36.95	25.11
Quake possibility (2005–2035)		2.01	0.57	4.04	0.31

Notes: Annual growth rate on residential/commercial land price are available for the municipalities in both HYOGO and OSAKA, though the land price data (in absolute value, as shown in Table 4) in OSAKA are missing.

Table 7: Population dynamic in terms of distance to Osaka

	(1)	(2)	(3)	(4)	(5)
	Annual rate of population growth (expressed as a percentage)				
Q*y9597*Dist	-0.021	-0.012	-0.034		-0.020
	(0.017)	(0.019)	(0.024)		(0.026)
Q*y9803*Dist	-0.071***	-0.091***	-0.098***		-0.099***
	(0.027)	(0.033)	(0.035)		(0.033)
Q*y9597	-0.649	0.049	-0.369	-1.330***	-1.201
	(0.513)	(0.438)	(0.659)	(0.353)	(1.638)
Q*y9803	2.459***	1.853***	3.206***	0.387	3.428*
	(0.647)	(0.493)	(0.848)	(0.421)	(1.972)
y9597*Dist	0.001	0.008	0.013		0.013
	(0.002)	(0.006)	(0.013)		(0.013)
y9803*Dist	0.006***	0.011	0.033*		0.033*
	(0.002)	(0.008)	(0.019)		(0.018)
Q*y9597*quake_prob.					0.334
					(0.532)
Q*y9803*quake_prob.					-0.072
					(0.634)
y9597*quake_prob.					0.243
					(0.236)
y9803*quake_prob.					0.041
					(0.335)
Constant	-0.030	-0.548**	0.028	0.028	0.028
	(0.217)	(0.237)	(0.261)	(0.263)	(0.262)
Municipality fixed effect	Y	Y	Y	Y	Y
Year fixed effect	Y	N	Y	Y	Y
Pref*Year fixed effect	N	Y	N	N	N
Overlap_dist_Osaka	N	N	Y	Y	Y
No. of treated/control muni.	20/64	20/64	20/48	20/48	20/48
N	1,344	1,344	1,088	1,088	1,088
R^2	0.121	0.243	0.134	0.080	0.139

Notes: Time period is 1988–2003. Control sample includes urban municipalities (cities and districts) in OSAKA (excluding Osaka), NARA, KYOTO, and WAKAYAMA. Robust standard errors are in parentheses (clustered at the municipality level)

* p < 0.1, ** p < 0.05, and *** p < 0.01.

Table 8: Estimates for land price

	(1)	(2)	(3)	(4)	(5)
	Annual rate of land price growth (expressed as a percentage)				
	residential	residential	residential	residential	commercial
Q*y9597*Dist	-0.067	-0.192***	-1.049***	-0.124*	0.008
	(0.048)	(0.064)	(0.208)	(0.061)	(0.095)
Q*y9803*Dist	-0.201***	-0.362***	-1.182***	-0.232***	-0.335***
	(0.047)	(0.068)	(0.183)	(0.053)	(0.123)
Q*y9597	5.276***	8.515***	41.452***	5.290***	2.199
	(1.790)	(2.201)	(7.436)	(1.823)	(3.151)
Q*y9803	8.518***	12.840***	42.692***	8.400***	11.456***
	(1.698)	(2.278)	(5.976)	(1.691)	(3.887)
y9597*Dist	-0.030***	0.095***	0.439**	0.024	0.016
	(0.009)	(0.036)	(0.210)	(0.037)	(0.070)
y9803*Dist	0.005	0.166***	0.370*	0.050	0.183**
	(0.011)	(0.044)	(0.207)	(0.040)	(0.093)
Constant	-2.862***	-5.004***	-19.906**	-2.747***	-11.453***
	(0.229)	(1.033)	(7.779)	(0.223)	(2.074)
Municipality fixed effect	Y	Y	Y	Y	Y
Year fixed effect	Y	Y	Y	Y	Y
Sample	All	All	District	City	All
Overlap_dist_Osaka	N	Y	Y	Y	Y
No. of treated/control muni.	20/64	20/48	9/9	11/38	20/48
N	924	748	198	539	731
R^2	0.683	0.723	0.779	0.762	0.509

Notes: Time period is 1993–2003. Robust standard errors are in parentheses (clustered at the municipality level)
* p < 0.1, ** p < 0.05, and *** p < 0.01.

Figure 1: Location of Hyogo prefecture, Japan

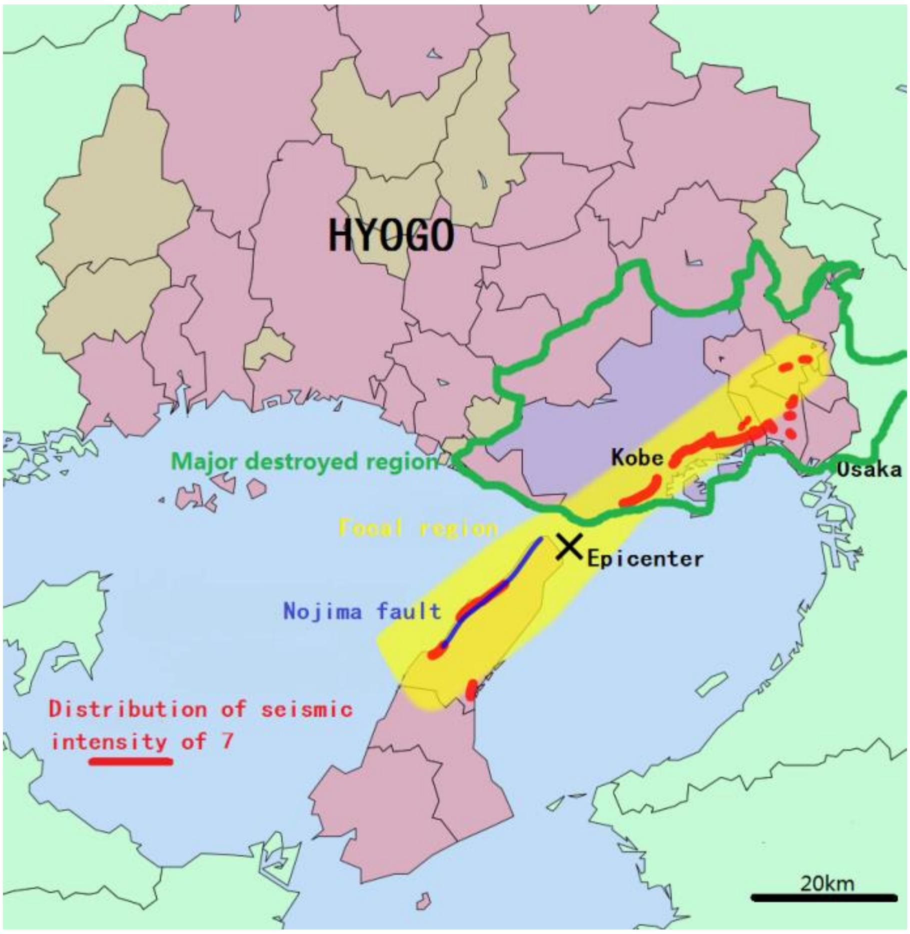


Figure 2: Location of epicenter and major destroyed region

Notes: The southwest part of the focal region is the Awaji island. However, I exclude it from the analysis since it is a rural area (during the study period, the Island comprised towns and villages, not cities and districts). The green bold line encircles 23 municipality-level cities and districts (details in Figure 8). Although the epicenter is in the west of Kobe city, owing to the spread of the earthquake wave, the distribution of a seismic intensity of seven is not absolutely restricted to areas close to the epicenter. Takarazuka, which is 35 km away from the epicenter, also suffered the earthquake measuring seven on the intensity scale.

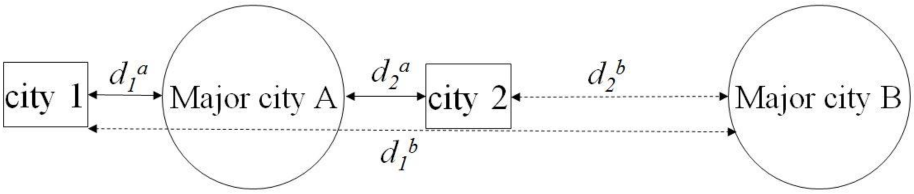


Figure 3: The location of small cities and major cities in the model

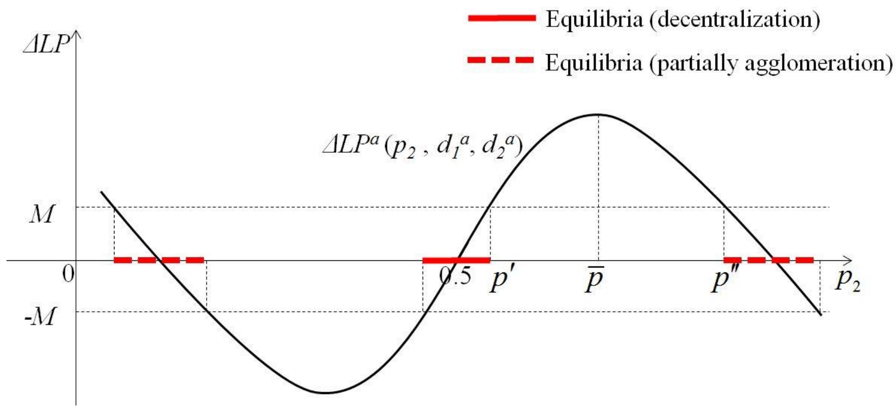


Figure 4: Equilibria of population distribution

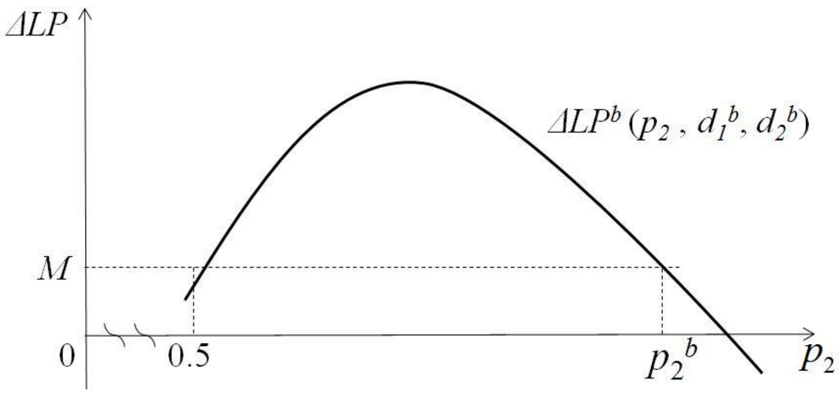


Figure 5: Equilibria of population distribution after earthquake

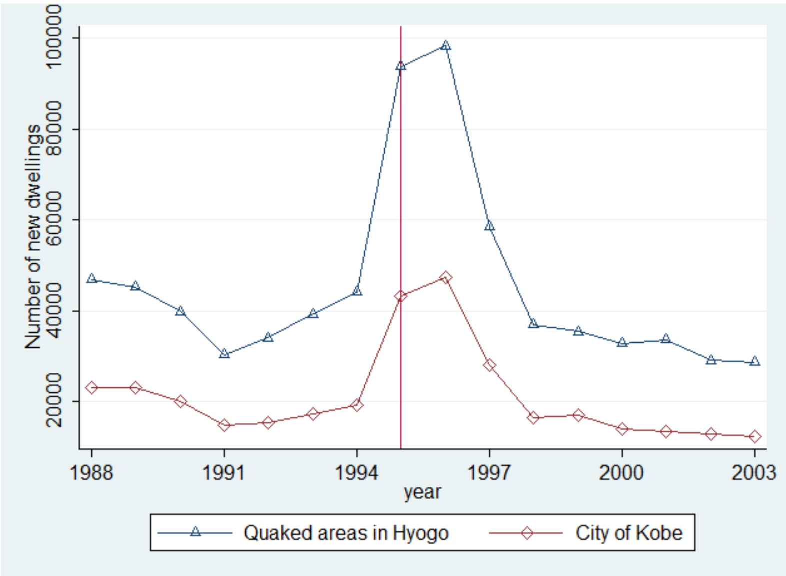


Figure 6: Number of new dwellings

Notes: Data refer to the number of new residential dwellings constructed in a specific year. Quaked areas in HYOGO include the 17 municipalities mentioned in Figure 8. Data for the quaked municipalities in OSAKA are not available. Data are from the Annual Report of Construction Statistics, annually released by the Section of Information Management, Policy Bureau, Ministry of Land, Infrastructure, Transport and Tourism.

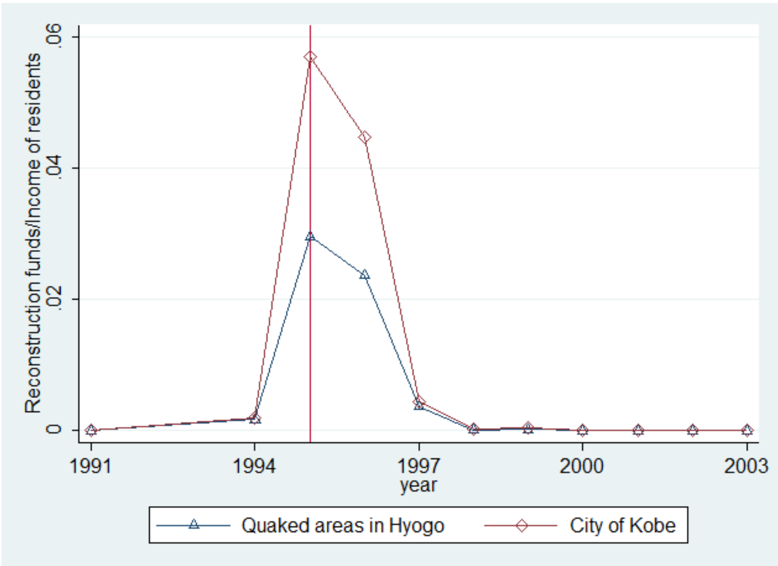


Figure 7: Reconstruction funds

Notes: The vertical line refers to the share of reconstruction funds in the total residential income: total reconstruction funds / total income of residents. Quaked areas in HYOGO include the 17 municipalities mentioned in Figure 8. Data for the quaked municipalities in OSAKA are not available. Data on reconstruction funds are from the Annual Report of Local Public Finance Statistics (available for 1991 and 1994–2003), Local Public Finance Bureau (LPFB), Ministry of Internal Affairs and Communications. Income data are from the annually released Residential Income Statistics from the Prefectural-Level Statistics Bureau.

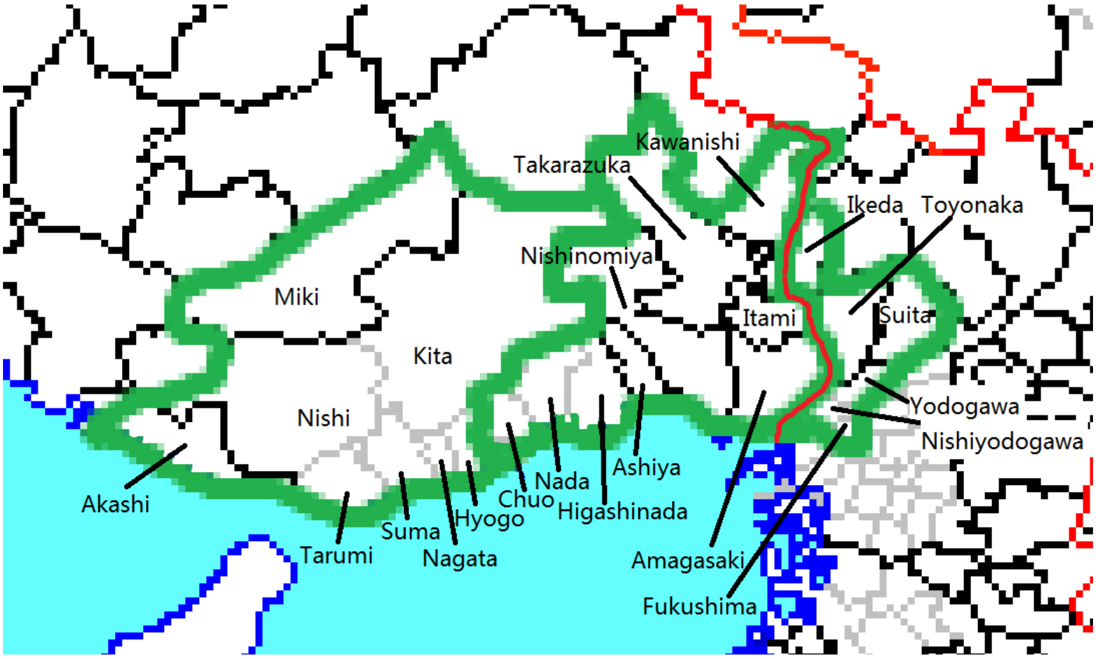


Figure 8: Municipalities in the major destroyed region

Notes: The area encircled by the green bold line consists of 23 municipalities. The left-hand side (eight municipalities) is the west of the quaked area in HYOGO, the middle (nine municipalities) is the east of the quaked area in HYOGO, and the right-hand side (six municipalities) is the quaked area in OSAKA. Data for Yodogawa in OSAKA are missing, and thus, are excluded from the analysis. All municipalities suffered an earthquake that was ≥5 on the intensity scale (more than half of the intensity scale observations within the area are no less than five) (Source: Japan Seismic Hazard Information Station). The black lines denote municipality-level city boundaries, grey lines are municipality-level district boundaries, red lines are prefecture boundaries, and blue lines are coastal lines. The land area of Kobe (nine districts) is 552 km^2. The land size of the total 22 sample municipalities are 1,172 km^2, of which 631 km^2 is the west area of HYOGO, 427 km^2 is the east area, and 114 km^2 in OSAKA.

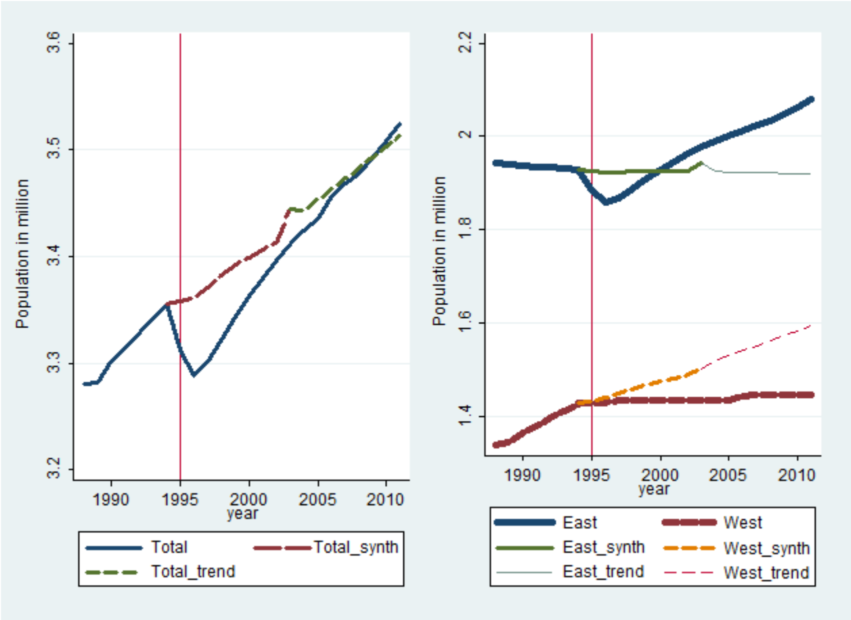


Figure 9: Population dynamics of the quaked areas in HYOGO

Notes: Total: the actual population size; Total_synth: the population size predicted by the synthetic controls; Total_trend: the population size predicted by the population growth trend (1988–2003). Although the administrative division at the municipality level was frequently merged after 2003, the quaked areas were not affected. The population in the quaked areas before and after 2003 is comparable.

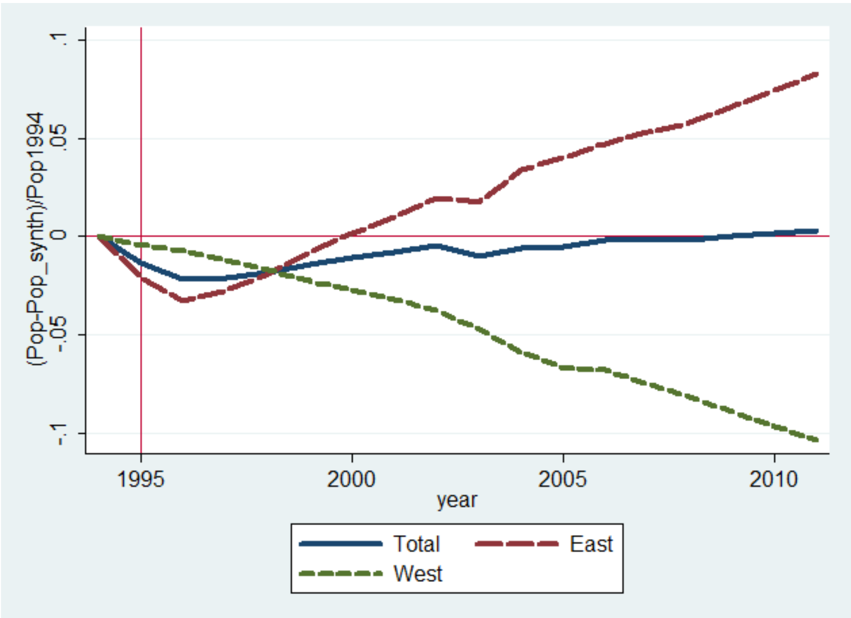


Figure 10: Population growth difference with synthetic control units

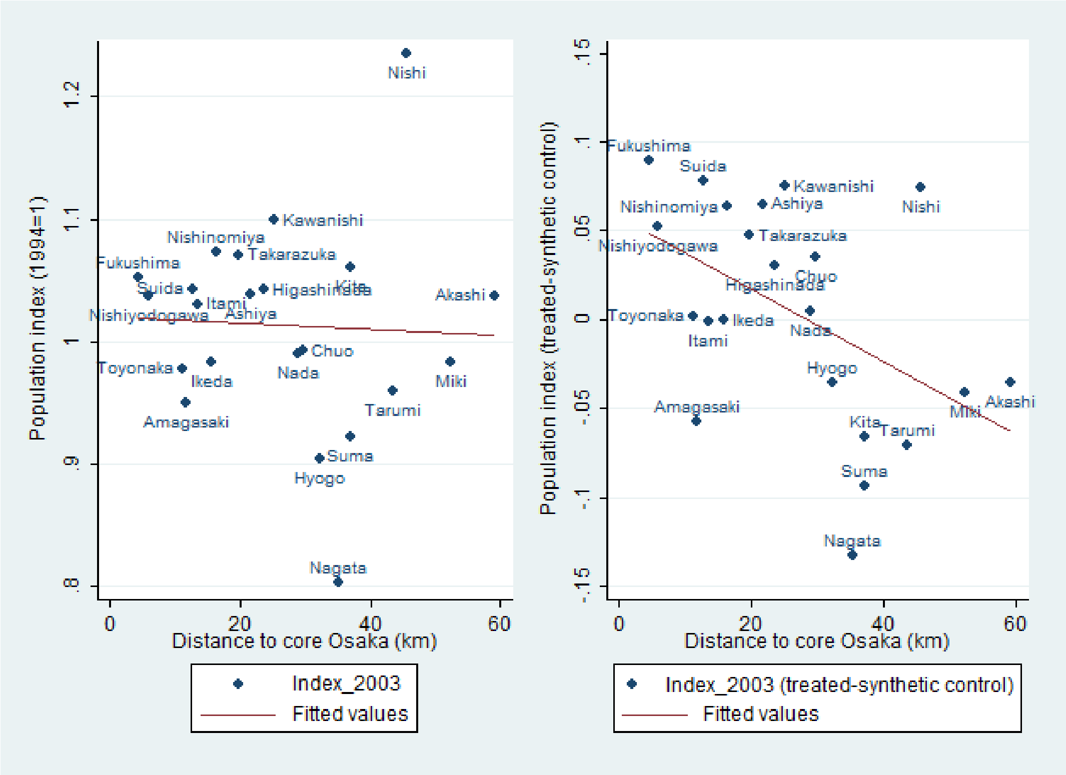


Figure 11: Post-quake population growth compared with synthetic control units

Notes: Distance is measured by the geo-code of Osaka station and the related municipality core areas.

Figure 12: Topography of the Kyoto-Osaka-Kobe MA

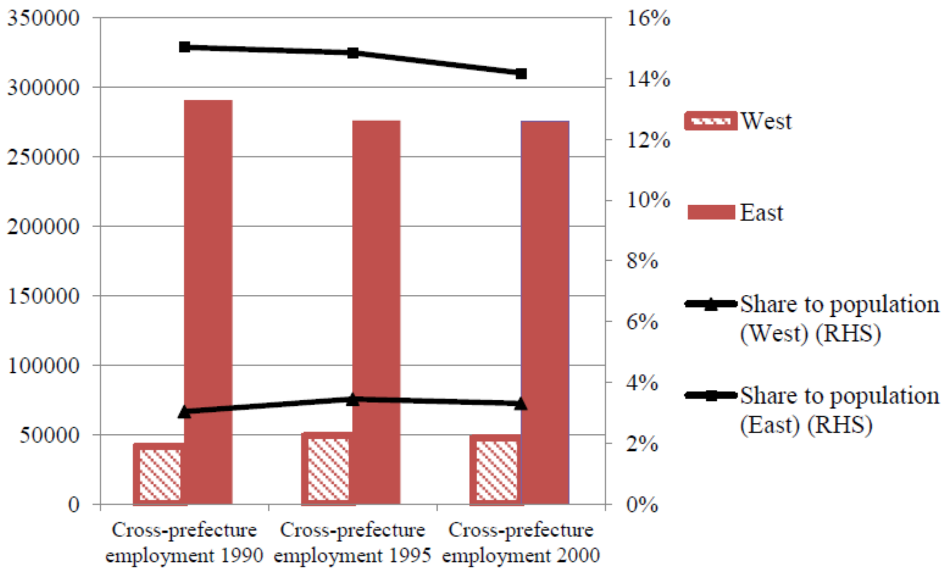


Figure 13: Cross-prefecture employment in quaked areas

Notes: Cross-prefecture employment: Number of residents in quaked areas of HYOGO who work in OSAKA. Data on cross-prefecture employment are from National Census (Kokusei Chosa) by the Statistics Bureau, Ministry of Internal Affairs and Communications, which is released at five-year intervals.

A.1 Data source

1) Data for residential population are from the Residential Population Survey by the Local Administration Bureau, Ministry of Internal Affairs and Communications.

2) Data on employment share and firm number are from the Establishment and Enterprise Census of Japan by Statistics Bureau, Ministry of Internal Affairs and Communications.

3) Data on aging index, land area, and cross-prefecture employment are from the National Census (Kokusei Chosa) by the Statistics Bureau, Ministry of Internal Affairs and Communications.

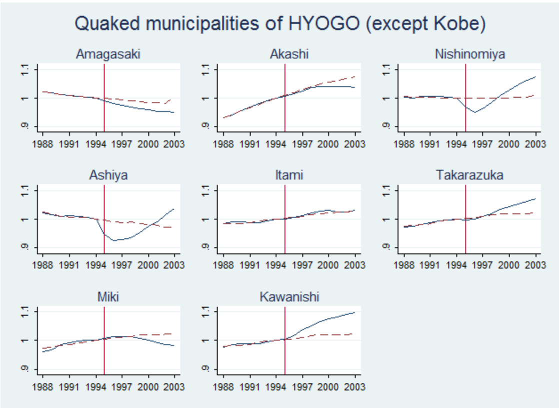
4) Data on the residential land price (absolute value) and growth rate of residential/commercial land price are from the prefectural statistics by Prefectural Statistical Bureau. Data on residential land price (absolute value) are missing for municipalities in OSAKA, thus land price was excluded from the predictors for the synthetic control approach for five treated samples in OSAKA.

5) Data on the possibility of a strong earthquake are from the Japan Seismic Hazard Information Station. The data are from January 1, 2005, and refer to the possibility of ≥6 intensity earthquake during 2005–2035. The possibility is counted in 1–5 by the quake probability: 0–0.1%, 1; 0.1–3%, 2; 3–6%, 3; 6–26%, 4; 25–100%, 5.

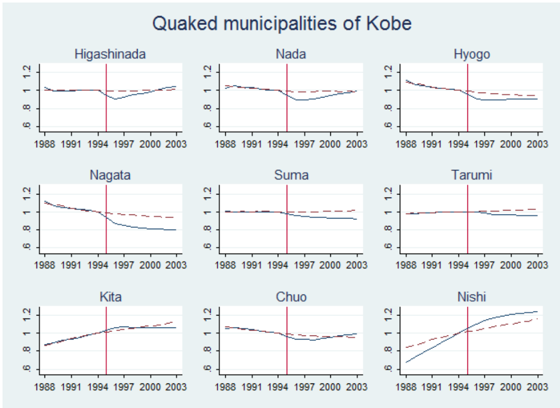
6) House destruction data for the 17 quaked municipalities in HYOGO are from Edgington (2010).

7) Longitude and latitude data (geo-code) for each municipality are obtained from the Center for Spatial Information Science, The University of Tokyo (CSV Address Matching Service), using which I calculate a municipality's distance to core Osaka.

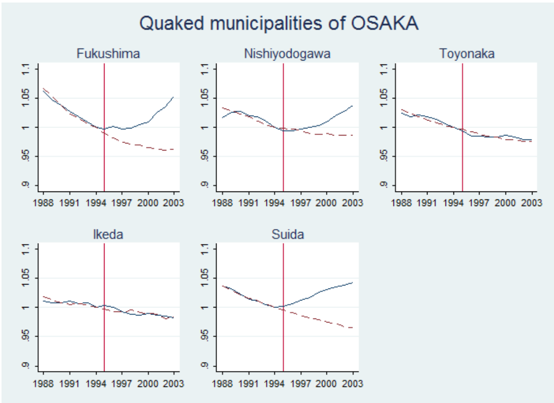
A.2 Additional figures



(a)



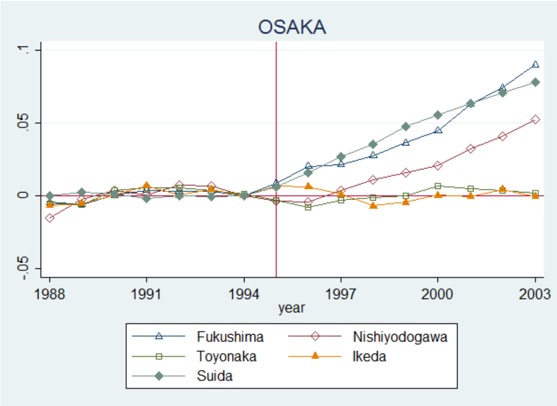
(b)



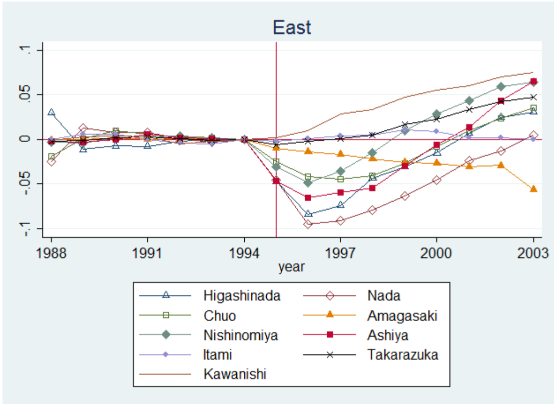
(c)

Figure A.1: Population index in quaked municipalities and synthetic control units

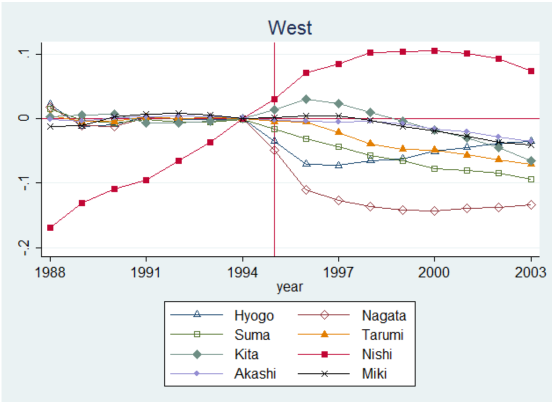
Notes: The solid lines represent the population index (year 1994=1) in the quaked municipalities. The dashed lines denote the population index in the synthetic control units.



(a)



(b)



(c)

Figure A.2: Population index difference between treated and synthetic control units

Notes: (a) OSAKA: five sample municipalities in OSAKA; (b) East: nine sample municipalities in the east side of the quaked area of HYOGO; (c) West: eight sample municipalities in the west side of the quaked area of HYOGO.

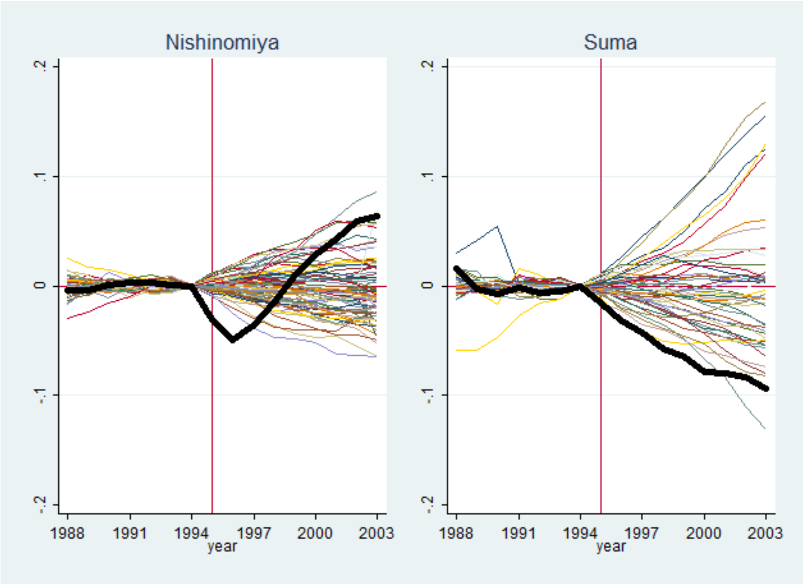


Figure A.3: Placebo tests (two examples)

Notes: The bold lines are the results for the treated sample and the remainders are placebo tests.

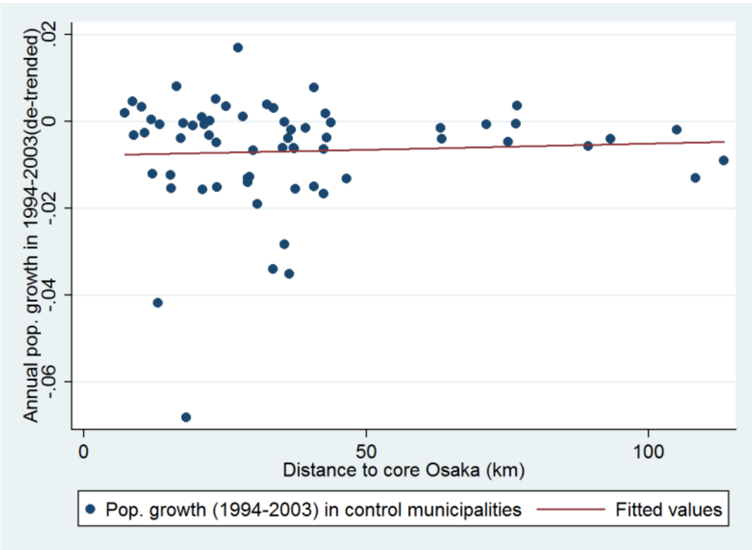


Figure A.4: Population dynamics in control municipalities of Kyoto-Osaka-Kobe MA

Notes: Annual population growth is calculated as (ln(pop,2003)-ln(pop,1994))/9. The population data in 2003 is de-trended using the data of 1988–1994. That is, I construct the pre-1995 linear trend of municipality-level population growth by using population data in 1988–1994 and then de-trend the original population data in 2003 by subtracting them with the population increase implied by pre–1995 trend.